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EVALUATING MIMA-MAC FOR DENSE URBAN ENVIRONMENTS

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REPORT DOCUMENTATION PAGE

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1.0 Summary

The importance of wireless communication for the military is substantial. A particularly challenging situation for wireless communication is the dense urban environment. One factor that makes such an environment challenging is that buildings and other urban objects cause shadowing of radio frequency (RF) signals, thus blocking reception. Another challenge is that such environments have substantial degrees of multipath interference due to reflections off of buildings and the variety of metal objects found in such environments. A final challenge lies in just the sheer number of devices that are likely to be deployed and finding a way for all of them to cooperate in a way to maximize overall performance.

    Countering these difficulties are improvements in the technologies underlying wireless communication and networking. Perhaps most fundamental is that Moore's law is making sophisticated signal processing cheaper and cheaper, both in term of silicon area and power. As a result, systems with increasingly sophisticated signal processing algorithms are practical.

    At the same time Physical layer (PHY) researchers have been developing a wide variety of techniques that leverage these new abilities. This report focuses on techniques that take advantage of having multiple antennas both for sending (output) and receiving (input). Although there are a wide variety of multiantenna techniques, the ones that this report focuses on are known as Multiple Input/Multiple Output or MIMO.

    Another important technology has been the focus of networking researchers. This is the use of multi-hop (often ad-hoc) wireless networks. In contrast to, for example cell systems, although a multihop wireless network may eventually reach an access point that has wired connectivity, in general information is transmitted through a series of wireless hops. There are many advantages to this, including providing solutions for the shadowing problem mentioned above.

2.0 The Mitigating Interference Using Multiple Antennas MAC

This report focuses on a technique, the mitigating interference using multiple antennas MAC (MIMA-MAC), which uses MIMO to solve a critical problem that occurs in multihop wireless networks. We show that applying MIMO to network level problems may result in novel uses of the basic technology. The end result is improved communication especially in dense urban environments.

    Here our goal is to give a high level overview of the MIMA-MAC. Thus we focus on the key ideas behind the system and attempt to abstract as many of the key insights as possible. More of the technical details about MIMA-MAC can be found in [1,2,3,4,5]. Minyoung Park's PhD dissertation [1] is the ultimate reference.

3.0 Multihop Wireless Network Problems

Let us consider what problems arise when wireless nodes carry flows of data across multiple hops. We assume a node that is typical of current technology, however relaxing

most of our assumptions about node capabilities would not change our basic analysis, but rather only make it more complex. We assume that nodes are homogeneous, half duplex, and use a carrier sense-based media access control (MAC) scheme. For a given power level, we assume that there is some maximum distance, T, that is the range for reliable transmission, and that the range for carrier sensing, C, is twice that for reception. In general, we also assume the nodes use the 802.11 DCF MAC, in which request to send (RTS) and clear to send (CTS) control packets are used to "clear the floor" for data transmissions.

Now consider a simple linear topology consisting of a variable number of hops, from 1 to N, where the distance between each node is a fixed value, D. Such a topology is a useful model of the sorts of paths that might be used in a real network. In such a topology, D cannot be larger that T. If it were the chain would be disconnected. Further, if we assume a shortest path routing algorithm, D cannot be shorter than 0.5T. If it were, the shortest path route could and would bypass an intermediate node.

Now let us consider what happens to flows as we vary the number of hops from 1 to N. For now we assume these flows are unidirectional and simply try to use as much bandwidth as possible. The 1-hop case is the best, it can potentially achieve transmissions rates equal to the channel capacity, C. For the 2-hop case, the half-duplex assumption means that each packet must be transmitted from both the source and the intermediate node and neither can transmit while the other one is. Thus the maximum rate is 0.5C. For the 3-hop case, there are two intermediate nodes. Because of carrier sensing, even if we are at maximum spacing, both intermediate nodes cannot transmit while the source is transmitting. Thus the maximum rate is 0.33C. For the 4-hop case at maximum spacing, neither carrier sensing nor the floor clearing CTS stops the third intermediate node from transmitting. This would seem like a good thing, but it is not. The reason is that at this spacing (an especially if the spacing is very slightly tighter) if the third intermediate node transmits during the sources transmission, it is likely to interfere with reception at the first intermediate node, resulting in a collision. If enough collisions occur in a row, the packet will be dropped. This problem is a manifestation of the fact that the 802.11 MAC does not fully solve the hidden node problem. It is not trivial to analyze the effect of this problem, but the best case is that the third intermediate node does not transmit, resulting in a rate of 0.25C. Analysis of more hops or closer spacing is not essential, the key point is that available bandwidth decreases until some limit is reached, and the possibility of collisions grows even greater.

The use of the Transmission Control Protocol (TCP) makes this problem worse because when a collision causes a packet drop, TCP views that as congestion and drastically slows its transmission rate. Enough drops an its rate is effectively zero. Further, the drops will likely also trigger the routing algorithm to try and find a new route. This both introduces overhead and causes more drops at the TCP level.

The end result is that the 802.11 DCF MAC is poor at supporting multihop wireless especially for TCP. This conclusion is further supported by [6]. Even if we had a better MAC, many of these effects would still apply because the need to eliminate interference would cause large numbers of nodes to stay silent while only one transmitted.

4.0 MIMO and Its Typical Uses

Recent research on wireless communications has shown that using multiple antennas on both the transmitter and receiver over a rich-scattering channel can increase either the capacity or reliability of a wireless link [7, 8]. Notice that dense urban environments represent exactly this sort of scattering environment. Two major techniques that exploit such capabilities are spatial multiplexing (SM) and spatial diversity (SD) [9]. SM increases the *capacity* of the multiple-input-multiple-output (MIMO) link by transmitting M_t independent data streams simultaneously from each transmit antenna and differentiating the data streams at the receiver with M_r (greater than or equal to M_t) receive antennas by employing a number of space-time interference cancellation algorithms such as a zero-forcing (ZF) or a minimum mean-square error (MMSE) or a maximum likelihood (ML) receiver [9]. On the other hand, SD schemes such as space-time trellis coding (STTC) [8] and space-time block coding (STBC) [10] increase the *quality* of a link by transmitting space-time coded data across both multiple antennas and time so that the receiver can have multiple copies of the same data, which experience independent fading. Since it is very unlikely for all the copies of the data to experience fading simultaneously, we can mitigate fading and increase the reliability of the link. The key point is that from the point of view of a single link, MIMO and related technology can increase the capacity of the link and/or mitigate fading.

5.0 The MIMA-MAC

The MIMA-MAC uses MIMO techniques in a novel way to address the problems of multihop flows. The key insight is that if a receiver could tolerate one potentially strong interferer then two things would be true. First, the problem with collisions could be avoided, since one interferer would not constitute a collision. Second, more transmitters could transmit concurrently in general because we would only need to prevent three transmissions in close proximity not two.

   The second key insight is that when using spatial multiplexing although the conventional approach has all the data steams coming from the same transmitter, it is quite feasible to have the streams coming from different transmitters. Now if we ignore all of the streams from transmitters we do not care about, this is the same as viewing them as interferers that we can cancel. If we have two transmit and two receive antennas, this says we can tolerate one strong interferer. Further note that the interferer can be canceled even if it is to far away to correctly transmit a packet. Thus in the scenario above the third hop node no longer creates collisions. Transmitting from two separate transmitters also allows us to transmit with full power from each antenna. If both streams came from the same node they would have to share the power budget. This results in a further increase in the signal-to-noise ratio.

   The actual MIMA-MAC applies these insights in a straightforward way, using 2x2 antennas. The idea is to first negotiate which two transmissions are allowed and then to actually do both at the same time. The protocol proceeds in four phases.

   First is a contention phase in which nodes that have packets to transmit send RTS packets in two rounds. Each round is similar to the normal operation of the 802.11 DCF

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MAC and if a node would have been granted the right to transmit with that MAC MIMA-MAC will also grant it that right in the first round. In the second round, the winners in the first round sit out. This allows potential second transmissions to attempt to also gain access. In practice, simulations show that for the topologies of interest, two transmissions are often allowed [1, 2].

Second is a phase where each transmitter that is allowed to transmit transmits a training sequence during the slot that corresponds to the round in phase one in which it was granted permission to transmit. The training sequences are used by the SD MIMO algorithms to separate the various streams.

Third is the data transmission phase. During this phase both transmitters transmit their data to their respective receivers. The SM algorithms separate the streams thus effectively canceling the interference. Since the data packets are generally longer than the control packets, this phase lasts much longer than the previous ones.

Fourth the receivers transmit ACKs in slots that correspond to which round they gained access in.

In [1-5] there are a variety of improvements proposed to the basic scheme above. For example, the control packets can be broadcast using SD techniques, while the data transmission can be enhanced by selecting which transmit antenna is best. Support is also added for small packets flowing in the opposite direction of the main flow. This enhances TCP performance. Although all of these improvements have some nontrivial impact, they do not change the basic key ideas or insights.

In [1] and [2-5] there are extensive performance studies, which we will summarize. The essential summary is that MIMA-MAC works. For a linear topology using TCP MIMA-MAC prevents the collisions that shut the TCP sending rate down and cause route outages. And it allows more simultaneous transmissions. As a result, as the number of hops becomes large (7-10) MIMA-MAC's performance levels out to be about 0.25C. In contrast an 802.11 system with essentially all the same improvements to the PHY as for the MIMA MAC, has better 1-hop throughput, but essentially no throughput at 7-10 hops because drops have cause TCP to reduce its transmission rate to essentially zero.

6.0 Conclusion and Final Speculation

In summary, we see that the MIMA-MAC holds great promise for dense urban environments. This is because of two things. First, the underlying MIMO techniques are very well suited for environments that have high multipath. Second, the MIMA-MAC uses MIMO techniques in a clever way to avoid key pathological situations at the network level, rather than just to enhance link capacity or reliability.

A final point of speculation. It seems likely that in dense urban environments, network topologies will include nodes that act as concentrators. These may be nodes that are connected to the wired infrastructure, or they may connect to some kind of wireless mesh backbone. It is likely that such nodes will have superior power resources and may be able to deploy more antennas. We can imagine a vehicle being used for such a node, with plenty of power and many locations for antennas. Although the MIMA-MAC work does not directly pertain directly to this particular topology, it seems likely that its insights can still be used. The problem with such a topology is that the concentrator node becomes a hot spot, with many nodes trying to send and receive data from it. The

observation is that even if the clients have only one antenna, if the concentrator node has multiple antennas then it can receive multiple streams, thus reducing the bottleneck and avoiding collisions.

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